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HIGH-LATITUDE GEOPHYSICAL STUDIES
WITH SATELLITE INJUN III[+]

PART IV: AURORAS AND THEIR EXCITATION

by

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ABSTRACT

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Photometric observations of auroras were made with the satellite Injun III at altitudes of 250 to about 600 km over North America early in 1963. Simultaneous observations of the precipitated electrons which caused the aurora and of trapped electrons were made with the magnetically-oriented satellite. The auroral zone, as defined on some fifty latitude surveys of the brightness of the N_2^+ emission at 3914 Å, showed an average maximum brightness of about 2 kilorayleighs at an invariant latitude (Λ) around 69° on the magnetic shell $L = 7.8$. Several visible auroras are discussed in detail. It is suggested that the auroras delineated the outer edge of the region of durable trapping of Van Allen electrons and that the electrons causing the auroras and having an isotropic angular distribution over the upper hemisphere at the satellite altitude were mostly freshly accelerated rather than old electrons of the Van Allen belts with similar energy. In two auroras measured by the satellite near perigee, less than 0.1% of the oxygen 5577 Å emission came from altitudes above 250 km. Hence, the flux of electrons of energy ~ 10 eV was no larger than the flux of those with ~ 10 keV. A U T H O R

INTRODUCTION

Many auroras are caused by excitation of atmospheric constituents by intense fluxes of charged particles. The most important bombarding fluxes are electrons with energy (E) of order 10 keV [McIlwain, 1960; Davis, Berg, and Meredith, 1960]. It is then of interest to find the cause of the bombarding particles, i.e., the mechanism that determines their spatial, temporal, and spectral characteristics [see review by Omholt, 1963]. Essential to such an investigation is knowledge of the "source" region from which the particles come.

When charged particles were found to be trapped in the geomagnetic field at radial distances up to some 40,000 kilometers [Van Allen, McIlwain, and Ludwig, 1959; Van Allen and Frank, 1959] it was often suggested that they might be such a source or a reservoir that, during a geomagnetic disturbance, would overflow and spill intense fluxes of charged particles into the atmosphere to cause an aurora. This concept in its simplest form came to be described as the "leaky bucket" model of the outer Van Allen zone.

One of us attempted to study the interrelation of the outer Van Allen zone and auroras by combining measurements of particles by the satellite Explorer VII with ground-based observations of auroras. In the eighteen-month life of the satellite, only one occasion (on November 28, 1959) was found when the satellite was over an aurora and when (a) adequate telemetry was being received; (b) the moon was not bright; and (c) a useful observer was nearly underneath the aurora with (d) his vision not obscured by clouds.

But besides the rarity of favorable conditions for such coordinated satellite- and ground-based observations, the particle detectors on Explorer VII were inadequate in several ways. They gave essentially no reliable information on either the particle type or energy, and they measured only omnidirectional particle fluxes so that we could not determine what proportion of the particles was trapped and, indeed, could not prove that any of the particle flux was actually plunging into the atmosphere. An attempt was made in the study [O'Brien et al., 1960] to deduce quantitative relations on the basis of then-current understanding of the particles causing a shielded Geiger to count in the outer zone. Our later studies have shown that the assumptions made in the analysis of these Explorer VII data were greatly in error.

A more satisfactory method of studying the interrelationship of outer zone and auroras is to equip a satellite with instrumentation to measure both. One of us [B. J. O'Brien] tried to do this with the State University of Iowa satellite Injun I. It was planned to orient one axis of the satellite parallel to the geomagnetic vector $\vec{B}$, and point a photometer down it to view the ground (or hopefully an aurora) while other directional detectors measured the particle fluxes. Injun I was launched on June 29, 1961, and operated for about eighteen months.

Unfortunately, however, a malfunction at launch prevented the intended separation of Injun I from the Naval Research Laboratory satellite Greb, although the separation from the other satellite in the triple launching (Transit IVA) did occur. Greb, housed in a twenty-inch diameter highly-polished aluminum sphere, completely fills the field of view of the Injun I photometer. Consequently, no useful auroral or airglow photometric data were obtained with Injun I although the photometer operated for the life of the satellite. (It is conceivable that the data could yield information about the effect on the aluminum reflectivity of eighteen months' bombardment by micrometeorites, but we have not made this analysis.)

The Injun I particle detectors did provide important information on the source of auroral particles, i.e., of those particles that bombard the atmosphere to cause auroras. They showed that the particles were precipitated from a source above the satellite altitude (viz., 1000 km), that high intensities were precipitated in the daytime as well as at night, and they indicated a crude similarity between the average latitude profile of precipitated electrons with $E_e \gtrsim 40$ keV and the latitude profile of occurrence of auroras viewed by ground-based observers during the I.G.Y. [For summary of relevant Injun I findings, see O'Brien, 1962.] But such statistical studies are clearly not as reliable as detailed analyses of individual events, since the phenomena are so variable.

Again an attempt was made to study auroras and the outer zone simultaneously by putting two photometers and several particle detectors on the satellite Injun II. This satellite was destroyed in an abortive launch on January 24, 1962.

So another attempt was made by putting three photometers and eighteen particle detectors on Injun III. This attempt has proven successful, and we report preliminary results in this note. The satellite is still operating at the time of writing (August 1963) and further studies of the data are being made.

A number of other studies have been made of the relationship between fluxes of charged particles and visible auroras. The first direct detection of particles associated with the auroral zone came in a series of rockoon experiments by the Iowa group [see review by Van Allen, 1957]. At altitudes of ~ 100 km, large fluxes of electrons of ~ 100 keV energy were found in the region of the auroral zone but not at higher or lower latitudes. There were no flights at night or during auroras.

Then during the I.G.Y. rockets were fired successfully into visible auroras. These found that large fluxes of low-energy electrons ($E_e \sim 10$ keV) were causing the excitation of the auroras [McIlwain, 1960; Davis et al., 1960]. The electron fluxes were found only in the regions emitting light. However, protons were found outside these regions as well as inside. The major contribution to the particle energy came from the electrons. McIlwain [1960] estimated that the total energy emitted as visible light was about 0.2% of the total electron flux.

An extended series of balloon-borne experiments also gives much information on association of auroras and particle fluxes bombarding the atmosphere. The Minnesota group [see Winckler, 1961] and the Iowa and California groups [see Anderson, 1960; Brown, 1961] made many flights at different latitudes. Generally speaking, the x-rays (caused by electrons bombarding the atmosphere) detected by the balloons displayed little correlation with visible auroras in the auroral zone, but at lower latitudes intense fluxes of x-rays were seen during great auroral displays.

Recently, balloon observations in the auroral zone have given evidence of some relations between x-rays and an auroral glow [Anderson and DeWitt, 1963]. The analysis indicated that in one event perhaps all the auroral glow could have been excited by electrons with energy $E_e \sim 10$ keV, whereas previous studies by the same workers suggested that distinct auroral arcs might have been caused by electrons with lower energies, undetectable by the balloon experiments.

A study was made of satellite (Explorer VI) observations of the outer radiation zone, and simultaneous balloon-borne detection of x-rays and ground-based sighting of auroras [Arnoldy, Hoffman, Winckler, and Akasofu, 1962]. Again the satellite detectors, like those in Explorer VII, were imperfect for quantitative studies of particle outflux. Clearly, simultaneous observation of both auroras and particles by instrumentation on the same satellite is desirable. Such observations are reported here.

Furthermore, the very techniques of observing auroras from a satellite afford possibilities for useful studies of the auroras themselves. For example, the concept of an "auroral zone" has been used for many years. As usually defined, this is the region where auroras are most common, in a zone around magnetic latitude $\lambda \sim 67°$ [Vestine and Sibley, 1960; Davis, 1962]. We will discuss in this note how the satellite-borne photometers make a latitude survey of auroral light several times each night, thereby enabling us to delineate "auroral zones" in essentially a time-stationary state.

EXPERIMENTAL APPARATUS

The satellite Injun III was launched on December 13, 1962 into an orbit with initial apogee altitude 2785 km, perigee altitude 237 km, period 116 minutes, and inclination 70.4°. The satellite is magnetically oriented, so that one axis is aligned with the local geomagnetic vector $\vec{B}$ [see O'Brien, Laughlin, and Gurnett, 1963, hereinafter referred to as Part I). Three photometers whose characteristics are listed in Table I have their optical axes parallel to this axis. Two of them view the ground at high latitudes in the Northern Hemisphere and the other views the ground at high latitudes in the Southern Hemisphere. At equatorial latitudes, they are all horizontal. Orientation in all studies made in this note was always within 4° to $\vec{B}$, and the two aspect sensors permit determination of the orientation to about 1° accuracy.

Each photometer is an Ascop type 541-A, selected for high gain and low dark current. Incident light passes through a two-inch diameter Baird-Atomic multilayer interference filter, then through a three-inch focal length converging lens. At the focus of the lens is the aperture defining the field of view of about ten degrees in diameter. The light then diverges and covers about fifty percent of the photocathode.

The spectral resolution of the filters is shown in Figure 1, and the angular resolution of the photometers in Figure 2. The filters were chosen to have wide passbands of about 50 Å for two reasons: (1) So that the temperature changes would not shift the wavelength of peak transmission away from the spectral emission wavelength, and (2) so that the emissions from the edges of the field of view would not be vignetted by the shift in the filter spectral passband due to the oblique angle of incidence.

The field of view was made about ten degrees wide so that even if payload orientation was several degrees away from alignment with $\vec{B}$ and even with a significant curvature of the field lines between the satellite and 100 kilometers altitude, the photometer field of view would still include that portion of the atmosphere bombarded by the particle flux whose characteristics were sampled by the satellite. The photometers may also see auroras caused by particle fluxes which passed several kilometers (or many cyclotron radii) from the satellite, and this must be recognized in the analysis which follows.

Electronic details and calibration of the photometers are described in Appendices I and II to this paper. Because this is the first report of observations of auroral light by satellite-borne apparatus, it is important to recognize possible causes of contamination of the data, and these are discussed in Appendix III. A plot of photometer data for one pass over North America is shown in Figure 3, and this illustrates two possible types of contamination.

In practice contamination of the data is minimized in several ways (see Appendix III). In particular, in this preliminary note, we study only auroral emissions, and subtract from the signal in each event a background signal estimated by interpolating between the constant signal on the low-latitude side of the auroral event and that on the high-latitude side. We therefore have subtracted not only thermionic dark current of the photometers and their enhanced dark current due to previous x-ray bombardment, but also any airglow contribution. The technique is illustrated in Figure 3 with a dashed line giving the level of contamination of the signal from New York.

No Southern Hemisphere data are reported here, but the Southern Hemisphere photometer is used in observations over North America to insure that thermionic and x-ray induced dark currents are negligible (see Appendix III). The temperature of a photometer is telemetered to the ground every four seconds, so that the thermionic dark current can be estimated accurately from pre-launch calibrations. The 5577 Å Northern Hemisphere photometer operates sometimes when the satellite is commanded on and power is applied to the detectors, but on many passes it does not. We attribute this intermittent behavior to intermittent starting of its high-voltage power supply or its analog-to-digital converter (see Appendix I), and when it does operate it gives data consistent with pre-launch calibrations.

In general, this study treats data mainly from the 3914 Å photometer, which has the advantages that any airglow contamination is negligible and that the light intensity emitted by the atmosphere is proportional to the auroral ionization and free of de-excitation effects /see Chamberlain, 1961/.

Several other detectors on Injun III are used in this investigation of the relations between particle fluxes and auroras. Only a brief description of these particle detectors is given here because they are described in detail by O'Brien, Laughlin, and Gurnett /1963/ in the paper called Part I. Their use in the analysis of the spectrum of electrons is described by Laughlin, Fritz, and Stilwell /1963/ or Part II. The dynamics of electron precipitation, which causes auroras, are discussed by O'Brien /1963/, in Part III. Association of particle precipitation, auroras, and very low frequency electromagnetic radiation is treated in Part V by Gurnett and O'Brien /1963/.

There are four detectors of particular interest for this note. Three are directional thin-windowed Geiger tubes that detect electrons with energy $E_e \gtrsim 40$ keV and protons with energy $E_p \gtrsim 500$ keV. The satellite is magnetically oriented, and one Geiger points back up along the geomagnetic field vector $\vec{B}$, another points at 130° to $\vec{B}$, and the other at right angles to $\vec{B}$. The three Geiger tubes detect particles whose pitch angle (α) is such that (a) $0° \leq \alpha \leq 43°$, (b) $37° \leq \alpha \leq 63°$, and (c) $77° \leq \alpha \leq 103°$, respectively. Particles in group (c) are generally trapped at most Injun III altitudes, and those in group (a) are generally in the loss cone, i.e., on their way down into the atmosphere. Those in group (b) are sometimes all trapped or all precipitated, or a mixture of both, depending on the satellite altitude or, specifically, on the local magnetic field B gauss. If we assume that the magnetic moment invariant is conserved below the satellite (see Part III) the pitch angle (α) of the particles at B is given by

$$\frac{\sin^2 \alpha}{B} = \text{constant}$$

and the loss cone is defined by α_D where

$$\frac{\sin^2 \alpha_D}{B} = \frac{1}{B_{100\ \text{km}}} .$$

The range covered by α_D over North America is tabulated in Part III.

The fourth particle detector of special interest here is the electron multiplier, which also points at $\alpha = 50°$. This has a thin nickel foil over it whose thickness ($86\ \mu g\ cm^{-2}$) is the same as the thickness of the residual atmosphere above about

120 km. Electrons and protons that can penetrate the foil and be detected therefore could have penetrated to auroral altitudes of around 100 km provided they were in the loss cone. In general for convenience this electron multiplier is referred to as a detector of electrons with energy $E_e \geq 10$ keV. In fact, it has a finite efficiency of detecting electrons with energies down to ~ 5 keV (see Part I). Other detectors on the payload can be used to derive the actual electron energy spectrum (see Part II).

The three directional Geiger tubes are used to derive a pitch-angle distribution for electrons with energies $E_e \geq 40$ keV, and it is assumed that this pitch-angle distribution is independent of energy for $E_e \lesssim 100$ keV (see Part III).

Other detectors on the satellite are used to establish that in all auroral events studied by us to date, electrons rather than protons are the dominant constituent in radiation of a given <u>penetrability</u>. We cannot exclude the possibility that there are say, as many protons cm^{-2} sec^{-1} with energy $E_p \sim 40$ keV as there are electrons cm^{-2} sec^{-1} with the same energy, but such protons are not as penetrating as such electrons. Therefore only electron fluxes are discussed below.

LATITUDE SURVEYS OF AURORAL LIGHT

Data discussed here came from moonless night passes over North America from January through March 1963 when the satellite was magnetically oriented (see Appendix III).

The counting rate of the 3914 Å is shown in Figure 3 for a mid-latitude pass over North America. In high-latitude passes, the signal always increases significantly in the vicinity of the auroral zone. In order to display many such results, the data in this note are plotted against a parameter (Λ) termed the "invariant latitude" [see O'Brien, 1962] derived simply from the L coordinate of McIlwain [1961] by the relation

$$L \cos^2 \Lambda = 1 .$$

The invariant latitude Λ is used here because the parameter L is found to be very useful in introducing order into studies of trapped particles [McIlwain, 1961] and because it is derived from a much higher order expression for (and hence, a more accurate description of) the geomagnetic field than is the usual expression of a magnetic latitude. Vestine and Sibley [1960] have discussed extensively the use of invariants of particle motion in plotting auroral zones, and the parameter Λ is a natural extension of their work, replacing their two coordinates B and I with one coordinate Λ .

In practice, over North America where the following data were derived, Λ differs from the geomagnetic latitude λ by generally less than two degrees, so the two may be treated as essentially the same for most purposes [see O'Brien, 1962].

Plots of three passes of the 3914 Å photometer over high latitudes are shown in Figure 4. These were chosen merely to illustrate the variability of the detailed latitude dependence of the 3914 Å emission, and the manner in which it always reaches a maximum somewhere in the vicinity of the classical auroral zone at invariant latitudes around $(67 \pm 5)^\circ$. Note that in Figure 4, the "background" signals have been subtracted from the photometer counting rates before they were plotted. In each case the background rates were less than ten counts per frame, so that the corrections had a negligible effect on all of the latitude profiles except the very faint edges of the emissions.

To provide a summary of about fifty such latitude profiles (not all of them over the complete range of latitude) a scatter diagram is shown in Figure 5. The variation in brightness at a given latitude in the auroral zone is large, but the scatter diagram reveals that there is always some 3914 Å auroral emission. A similar scatter diagram of precipitation of electrons with $E_e \geq 40$ keV shows that there is also always precipitation in the auroral zone (see Figure 16 and associated discussion in Part III).

For convenience, and to provide a summary, the data of Figure 5 were used to obtain both a median intensity and an average intensity latitude profile of auroral light. These are shown in Figure 6, together with the auroral zone fitted by Vestine [1944] from visual observations of auroras.

The curve of Vestine [1944] is not really comparable with our curves because it depicts auroral isochasms, representing locations where auroras can be seen anywhere in the sky, rather than isoaurorals where the auroras are plotted if they are overhead, or, as with Injun III, underneath. Furthermore, Vestine's curve has been shown [Vestine and Sibley, 1960] to be a few degrees too far north in the vicinity of Hudson's Bay, where many of the Injun measurements were made. Also, of course, the physical significance of curves such as that of Vestine is not at all clear, because they do not refer to an instantaneous probability of seeing an aurora, but rather to the probability of seeing one any time during a night. Other studies, such as that of Roach et al. [1960] refer to shorter time constants; for example, fifteen minutes or so. The Injun III observations refer to times of the order of a few seconds and, therefore, approach very closely the desired concept of an instantaneous measurement. The raw data are shown in Figure 5, so that a probability of the auroral emission being above a certain threshold (e.g., the visual threshold) can be derived by the reader. The data presented here contain the additional information (which is lost in any curve such as Vestine's) about the intensity of the phenomena.

These preliminary findings can be summarized by stating that during January and February, 1963, over North America, the maximum average intensity and the maximum median intensity of auroral 3914 Å light occurred on the magnetic shell $L = (7.8 \pm 0.7)$ or at an invariant latitude $\Lambda = (69 \pm 1)°$. The latitude profiles were about 5° wide at half the peak intensity.

During the night of February 28, 1963, the 5577 Å Northern Hemisphere photometer operated on command over College, Alaska. Plots of its counting rate are shown on a map of the satellite trajectory in Figure 7, so as to illustrate the spatial extent of typical latitude surveys. The field of view of the photometer is also shown in the figure. In Figure 7, no attempt has been made to subtract a background counting rate. It can then be seen how the counting rates tend to become constant on each side of the auroral events. This constant level is dominantly due to the airglow emission at 5577 Å, as in these cases the contamination of the 5577 Å photometer due to thermionic and x-ray-induced dark current was less than ten percent of the airglow signal. The airglow was estimated to be about 300 rayleighs, which is a reasonable value [see

Roach et al., 1960]. Unfortunately, clouds obscured ground-based observations of these auroras, although some auroral light was detected [G. Romick, private communication].

One of the interesting problems in auroral and airglow studies is simply to determine the relative contribution of each phenomenon in a given emission, and indeed to ascertain whether the two phenomena are actually different in the sense that they have different origins [see Roach et al., 1960; and Chamberlain, 1961]. In this note a signal is deemed to be from airglow if it is weak (less than ~ 500 rayleighs). One of the features generally used to discriminate between aurora and airglow is the ratio (R) of the intensity of 5577 Å to the intensity of 3914 Å. The 5577 Å emission from atomic oxygen requires an excitation energy much less than the 3914 Å from ionized molecular nitrogen, and the fact that R is $\gtrsim$ 10 in airglow but of order unity in aurora is often cited as evidence that airglow is excited by chemical means while an aurora is excited by particle bombardment [see Chamberlain, 1961]. While the interrelation of aurora and airglow is not examined in detail here, 3914 Å and 5577 Å intensities are plotted against one another in Figure 8, for the two passes shown in Figure 7. The numbers plotted are the instantaneous intensities of 5577 Å and 3914 Å minus the background signal including airglow for each. Thus the plotted data are brightnesses of each auroral emission throughout the two auroral events.

The plotted points lie about a line with a forty-five degree slope, i.e., a line drawn on the assumption that R is constant throughout an auroral pass and from one pass to another. Figure 8 provides an added measure of confidence in the response of the 3914 Å photometer.

SIMULTANEOUS OBSERVATION OF PARTICLE FLUXES AND AURORA

As the photometers on Injun III point down $\vec{B}$ to view an aurora, other instrumentation on the satellite measures the precipitated particles causing the aurora, and also trapped particles that are mirroring near the satellite altitude. Samples of such measurements are shown in Figures 9 and 10. The only particle data plotted in these figures are those obtained by the Geiger counters, measuring electrons with energy $E_e \gtrsim 40$ keV. While the electron multiplier and the d.c. scintillator show significant responses at the peak of the auroral emissions, their sensitivities are so low that the dynamic range they cover is only about an order of magnitude in these events, while the Geiger tubes and the photometers vary over two to four orders of magnitude. The response of the electron multiplier for such events is discussed in Part II, and we make use of that treatment here.

Consider first the electrons with $E_e \geq 40$ keV. In Figures 9 and 10 it can be seen how the flux of trapped electrons (with $\alpha \sim 90°$) is large (of order 10^4 to 10^5 particles cm^{-2} sec^{-1} $sterad^{-1}$) at midlatitudes, as usual (see Parts II and III). The flux of these particles increases greatly in the general vicinity of the aurora, and then decreases by a factor of one thousand or so at the high-latitude boundary.

The flux of precipitated or "dumped" particles was estimated in Figure 9 from the Geiger tube detecting particles with $\alpha \sim 50°$, and in Figure 10 from that detecting particles with $\alpha \sim 0°$. At low latitudes or $2 \lesssim L \lesssim 3$ in Figure 9, particles with $\alpha \sim 50°$ were actually trapped at the satellite altitude. The flux of precipitated electrons in both passes may therefore be considered to rise from low levels ($j \lesssim 10^3$ or perhaps 10^2 particles cm^{-2} sec^{-1} $sterad^{-1}$) at midlatitudes, to very large fluxes over the aurora, then to decrease at higher latitudes in much the same manner as do the fluxes of electrons with $\alpha \sim 90°$, the so-called "trapped" particles. (We discuss below and in Part III the extent to which they are truly trapped.)

In Figure 10, the lower-energy electrons (with $E_e \gtrsim 10$ keV) reached their maximum flux within two seconds of the time (i.e., the time in the satellite frame of reference) when both the electrons with $E_e \geq 40$ keV and the auroral light were at their maximum intensity. The electron energy spectrum was very much harder in Figure 9 than in Figure 10, and no useful detailed analysis of electrons with $E_e \gtrsim 10$ keV can be made for Figure 9. In fact, the peak flux of electrons with $E_e \gtrsim 10$ keV was about three times larger in Figure 10 than in Figure 9 even though the flux of electrons with $E_e \gtrsim 40$ keV was about ten times smaller. This great difference in the electron spectrum (which may be associated in part with the different latitude of occurence) makes detailed comparison of the events impractical.

A further problem in analysis of the interrelation of particle fluxes and auroral light arises because some of the auroral light is generated by particles that passed many cyclotron radii away from the satellite, and suc' particle fluxes conceivably can be quite different from the flux analyzed by the satellite instrumentation.

Nevertheless, we consider that several generalizations can be made from analysis of many passes such as those shown in Figures 9 and 10.

First, auroral light is emitted from those regions where intense fluxes of electrons are bombarding the atmosphere. From Injun I and Injun III observations, these electrons are generated at altitudes above ~ 1000 km.

Second, the energy spectra of electron fluxes causing auroras can vary enormously, both during a satellite pass and from one pass to another. (See also Part II.)

Third, the electron fluxes over an aurora tend to be isotropic over the upper hemisphere when measured at altitudes between ~ 250 km and at least 600 km (see also Part III). This implies that the flux is probably isotropic when it bombards the atmosphere at an altitude of ~ 100 km [see also Davis et al., 1960].

Fourth, the aurora is brightest near the high-latitude boundary of "trapped" particles.

Fifth, the low-latitude edge of an aurora begins in the region where significant precipitation of electrons with $E_e \gtrsim 40$ keV is occurring, but there is some indication that a weak portion of the aurora may persist to higher latitudes than does such precipitation. Auroral light in such high-latitude regions may be excited by low-energy ($E_e \sim 10$ keV) electrons in fluxes too small to be measured in this experiment. This would imply that the electron energy spectrum has a tendency to be softer at higher latitudes [see also Part II and O'Brien, 1962].

COMMENTS ON THE ENERGY SPECTRA

As stated above and by other workers [e.g., McIlwain, 1960] the energy spectra of electrons causing auroras change during an event and from event to event. Relatively little theoretical work has been done on the significance of these spectral observations. McIlwain [1960] suggested that his detection of what was essentially a monoenergetic flux in one event might imply that an electrostatic acceleration mechanism was at work. One of the features of auroras relevant to these considerations is the fact that most auroral arcs are brightest at altitudes of around 100 to 110 kilometers [see Chamberlain, 1961]. An immediate implication is that perhaps the electrons generally have at least a few kilovolts of energy, sufficient to penetrate to such depths in the atmosphere. Such a conclusion would clearly be important in studies of possible source mechanisms. But study of electrons with energy between a few eV and a few keV is technically difficult, and relatively few direct measurements have been made. Davis et al. [1960] showed in rocket flights that the spectrum did not steepen greatly at low energies of a few tens of eV, but their measurements were near their limit of resolution.

The upward-viewing and the downward-viewing 5577 Å photometers in Injun III were both operative when the satellite passed above the maximum brightness of the two auroras on February 28 indicated in Figure 7. The satellite was near perigee, at about 250-km altitude, at the time, so that the relative intensities of 5577 Å emitted above and below 250-km altitude can be determined. In these two events, the counting rate of the upward-viewing photometer changed by $(+4 \pm 4)\%$ in the first pass and by $(0 \pm 4)\%$ in the second pass at the locations of the peak brightness. These results are consistent with zero changes, and they show that the intensity of 5577 Å light emitted above 250-km altitude was less than about 0.1% of that emitted below 250-km altitude. This implies that the number flux of 10 eV electrons is no larger than the number flux of 10 keV electrons causing the main auroras. Yet the energy spectra are relatively steep at energies above $\sim$ 10 to 20 keV. These facts must be explained by any theoretical acceleration mechanism.

ENERGY FLUXES PRECIPITATED IN AURORAS

The average maximum intensity of 3914 Å was about $(2 {}^{+4}_{-1.6})$ kilorayleighs. (See Appendix II for discussion of the accuracy of this estimate.) From such a measure we can estimate the average energy flux of electrons precipitated into the atmosphere at the same location. Chamberlain [1961] quotes estimates that about 2% of the ionizing collisions result in excitation of N_2 to give 3914 Å, and if we take 35 eV as the average energy loss per collision, then the average energy flux of electrons precipitated into the atmosphere at $\Lambda \sim 69°$ is calculated to be 5 erg cm^{-2} sec^{-1} for a 3914 Å brightness of 2 kilorayleighs. Such an energy flux is in agreement with the estimates derived directly from particle measurements alone [see O'Brien, 1962, and Part III]. These particle measurements from both Injun I and Injun III found an average precipitated flux of electrons with $E_e \geq 40$ keV to be $\sim 4 \times 10^5$ particles cm^{-2} sec^{-1} in the auroral zone, and that the associated flux of electrons with energy $E_e \gtrsim 1$ keV is about 4 ergs cm^{-2} sec^{-1}. These numbers should be considered as accurate to a factor of about three.

These results show that the average energy required to sustain auroras and high-latitude particle precipitation around the world is of order 10^{18} ergs/sec. By comparison, the average energy brought to the front of the magnetosphere by the solar wind is of order 10^{20} ergs/sec.

Only one previous experiment has measured the efficiency of excitation of auroral light directly. McIlwain [1960] found that the energy flux emitted as visible light was about 0.2% of the total energy deposited by electrons. The excitation efficiency is not discussed in detail here because the calibrations of the satellite instruments are still being refined and because the particle detectors and the optical detectors sample fluxes over very different dimensions (or order 100 meters for the particles and 40 km for the light). However, our preliminary values for the excitation of light indicate an excitation efficiency more nearly one percent than one tenth of one percent. Theoretical estimates predict an efficiency of order one percent [see Chamberlain, 1961]. These results are only preliminary and further studies are being made.

It is useful to note here that about ten percent of the electrons with $E_e \geq 40$ keV being precipitated are backscattered by the atmosphere (see Part III). If these are able to travel to the opposite hemisphere without significant perturbation by the acceleration mechanism that generated them in the first place, they will produce ionization and aurora near the conjugate point. This effect may be negligible if acceleration mechanisms cause primary precipitation in both hemispheres at near-conjugate points, as the data from balloon-borne detectors indicate [Brown, Anderson, Anger, and Evans, 1963].

INTERRELATIONS OF AURORAS AND VAN ALLEN RADIATION

It has been apparent for some years that dynamic mechanisms must accelerate electrons in the magnetosphere so that precipitation ensues to cause an aurora. The concept of the "leaky bucket", wherein trapped electrons have their trajectories placed in the loss cone without their being energized, is inconsistent with many observations (see discussion in Part III). We examine briefly here what the interrelation of auroras and Van Allen electrons may be, although any such discussion is essentially in the hand-waving stage because detailed theoretical models do not exist to be tested. The dynamics of particle precipitation and the acceleration mechanisms are discussed in Part III.

From Figure 5 and from many previous studies [Chamberlain, 1961] it is seen that auroras occur not only in the usual auroral zone around $\Lambda \sim 69°$, but also at much lower latitudes. The low-latitude auroras occur during large magnetic storms. Similarly, the high-latitude boundary of trapping of Van Allen electrons occurs commonly in the auroral zone, but during large magnetic storms it moves to lower latitudes. Furthermore, both the aurora and the boundary of trapping show similar diurnal variations in their movement in latitude, occurring some 5° closer to the equator around midnight than during the day. So both phenomena show similar spatial behavior on a statistical basis.

Figures 9 and 10 show that the similarity exists also in individual events, where Figure 9 applies to a low-latitude aurora. The study with Explorer VII in 1959 [O'Brien et al., 1960] showed a similar effect, in that case at $L \sim 3.1$ or $\Lambda \sim 56°$, which is a very low-latitude event. The planetary magnetic disturbance index at that time was $K_p = 8$.

From Figures 9 and 10 and from the discussion of Part III, it is apparent that not only is the flux of precipitated electrons large over an aurora, but so is the flux of electrons moving at right angles to $\vec{B}$ at the satellite altitude between ~ 250 and ~ 600 kilometers. It is generally considered that if a particle mirrors at such altitudes then it is trapped and hence, by definition, a valid constituent of the Van Allen radiation. But it is not at all evident that it will necessarily bounce all the way to the opposite hemisphere, mirror there and return again, passing unperturbed through the regions where particles are being accelerated.

It was shown in Part III that electrons with energy $E_e \sim 1$ MeV could still be trapped and essentially be unperturbed on the field lines which were guiding centers for precipitated electrons with $E_e \sim 50$ keV. This could be proven only for those magnetic shells on which 1 MeV electrons were found in large intensities, i.e., around $L \sim 3$ to 4. It was suggested that it might hold also in small precipitation events at higher values of L (see Part III) but it could not be proven there. Now the fact that the flux of electrons with $E_e \geq 40$ keV tends to approach isotropy over the upper hemisphere during intense precipitation suggests that electrons with pitch angles $\alpha \sim 0°$ and $\alpha \sim 90°$ are subject to similar influences in their latitudinal travels through the magnetosphere. But most of the electrons with $\alpha \sim 0°$ are lost in the atmosphere immediately. So it appears unlikely that the particles with local $\alpha \sim 90°$ could remain unperturbed and bounce to and fro in latitude many times while their flux was being continually augmented as more electrons were precipitated and more were accelerated to $\alpha \sim 90°$. What we are suggesting is that electrons with energy $E_e \sim 50$ keV can be trapped with $\alpha = 90°$ on a field line before, during, and after precipitation, but different individual electrons are involved in the three cases.

This discussion might be clarified if we chose to adopt a model for the acceleration mechanism. For example, it could be assumed that an electric field of some tens of kilovolts might be temporarily established at high altitudes parallel to the geomagnetic field $\vec{B}$. Then, as a rebuttal to those who would suggest since it is impossible to maintain such an electric field that it cannot exist, we would suggest that the very short-circuiting of such an electric field is the precipitation phenomenon we study. Then we might set up a transport equation with variable parameters such as the location and magnitude of the electric field, the temporal behavior of its growth, endurance, and decay, the initial pitch-angle distribution and energy spectrum (including thermal electrons). As a result, we might obtain the final electron pitch-angle distribution and energy spectrum as functions of time, and compare them with Injun III data. Clearly there are so many variable parameters and so mutable a model that useful testing cannot be carried out here.

It has been suggested [e.g., O'Brien, 1962] that in the auroral regions the primary acceleration mechanisms which cause precipitation also give a finite increase in the flux of trapped particles. This speculation is discussed extensively in Part III, and it is shown to be consistent with the observations made. This leads to the implication (see Part III) that, instead of primary Van Allen electrons being the cause of auroras, some Van Allen outer-zone electrons are caused by the (unknown) mechanisms that cause auroras.

It is apparent that few satisfactory conclusions can be drawn at present about the exact interrelations of auroras and Van Allen radiation. It is clear that the second is not the immediate cause of the first. It is also clear that the Van Allen zone is bounded approximately by the same geomagnetic field lines that pass through the aurora. Further significant understanding of the relations will follow only when more extensive experimental information is available about the particle dynamics, including the dynamics of thermal electrons and protons, at high altitudes near the boundary.

CONCLUDING COMMENTS

Many auroras are caused by electrons precipitated from altitudes above several hundred kilometers. Results from Injun I imply that the source lies at an altitude above 1000 km [O'Brien, 1962]. The inner (or low-latitude) edge of the major part of the aurora defines the outer (or high-latitude) boundary of durable trapping of electrons with $E \geq 40$ keV, and although electrons of these energies can be trapped (perhaps for many bounces) beyond this boundary, they will be significantly perturbed and some may be lost when a precipitation event occurs in the same region. Most of the auroral excitation, however, is judged to be caused by freshly-energized electrons which were accelerated down the magnetic field lines. The acceleration mechanism is unknown. At altitudes from 250 km to about 600 km above an aurora during intense precipitation, the pitch-angle distribution of electrons with $E_e \geq 40$ keV tends to approach isotropy over the upper hemisphere, and about 10% are backscattered after being precipitated. It is not known whether the energy spectrum is a function of pitch-angle, but the evidence suggests that the electrons causing an aurora bombard the atmosphere as an isotropic flux over the upper hemisphere.

The average maximum intensity of 3914 Å emission in the auroral zone over North America was about $(2\ ^{+4}_{-1.6})$ kilorayleighs in the first two months of 1963. There was always some emission, often subvisual, in auroral regions just as there is always a finite flux of precipitated electrons (see Part III). Both from optical and particle studies, it is estimated that the average flux of particles precipitated in the auroral zone is about 3 to 5 ergs cm^{-2} sec^{-1}. The instantaneous flux occasionally is as large as 2000 ergs cm^{-2} sec^{-1} [McIlwain, 1960; and O'Brien, 1962].

The latitude profile of the N_2^+ 3914 Å emission displayed a maximum intensity at an average invariant latitude $\Lambda \sim (69 \pm 1)°$ or on the magnetic shell $L = (7.8 \pm 0.7)$.

There is clearly a need for further rocket and satellite measurements to investigate the nature of the magnetospheric boundary and the boundary of trapping, and for theoretical treatment of acceleration mechanisms and the process of energy transfer from the solar wind.

ACKNOWLEDGEMENTS

Extensive use has been made in this note of data obtained with several Injun III detectors, and we acknowledge the assistance of D. Stilwell, L. Frank, and J. Craven. Messrs. C. D. Laughlin and D. A. Gurnett were responsible for much of Injun III, and J. Gardner for some of the photometer design and construction. We thank Dr. J. A. Van Allen and Dr. A. J. Dessler for helpful discussions about our findings, and Dr. Van Allen for his sympathetic assistance of the whole Injun III program. We also thank Dr. Franklin Roach of the National Bureau of Standards Laboratories in Boulder for his assistance in the calibrations and general discussion. The Office of Naval Research, and particularly Dr. J. Fregeau, have made it possible finally to obtain photometric studies of an aurora by funding in large part the three Injun satellites. The National Aeronautics and Space Administration has also supported the project, particularly with tracking and telemetry, and we thank Mr. W. Lew for his help. Telemetry was also received by the Prince Albert Radar Laboratories and the National Research Council of Canada, and we thank Drs. D. C. Rose and R. S. Rettie and Mr. D. Hansen for their assistance.

APPENDIX I

Description of the Photometers

The three photometers on Injun III are of similar mechanical and electronic design. Each is a self-contained assembly, requiring only a power input from the nominal 24-volt satellite battery and the nominal 6-volt satellite battery. Each provides a pulsed or digital output to the appropriate accumulator (see Part I). The optical system was discussed in the text. Each photometer weighs about one pound and uses about 200 milliwatts of power when the satellite is commanded on.

A photometer is operated at about 2500 volts negative potential, with the anode grounded. The high-voltage is generated from a 24-volt D.C. supply direct from the satellite battery by using a D.C.-A.C. converter, a saturating-core transformer, and a Cockcroft-Walton array. High-voltage is regulated by a corona tube, and the variation is less than $\pm$ 1% over a temperature range of -30° to +45° C and a battery input voltage range of 20 to 26 volts. These ranges are about twice those encountered in flight, and so no correction has been made specifically for voltage or temperature effects on the high-voltage supply. In practice, throughout this study of auroral phenomena, the steady-state low- and high-latitude signals have been subtracted (see text and Appendix III).

Since the photometers are always switched on when the payload is commanded to operate, they very often view the sunlit earth or clouds, which have a brightness very much greater than a bright aurora. Two safeguards to avoid damage to the tubes and subsequent increased dark current were taken. First, the dynode resistors were chosen to be 33 Megohms, so that when the current through the final stages of a phototube approaches the 5 microamperes available in the parallel resistors, it will tend to short out the resistor, decrease the voltage across it, and hence decrease the gain of the phototube. This would be of relatively little use except that a second step in the design was to limit the total current available from the power supply to about 20 microamperes.

As a consequence, the signal current from the photomultiplier is not proportional to the intensity of incident light. However, the characteristics of the photometers could be matched to the phenomena being studied, so that they were linear for airglow and weak aurora, but non-linear for intense aurorae and, of course, the sunlit earth.

The signal current of each photometer is fed to a 50 $\mu\mu f$ capacitor which charges up to a voltage sufficiently high to trigger a neon glow tube. The analogue signal is then converted to a digital series of pulses, which are amplified and shaped before being fed to the twelve-bit accumulators each photometer has in each telemetry system. The counting rate is proportional to the signal current.

Generally the two 5577 Å photometers are sampled four times a second, and the 3914 Å photometer once every two seconds. The 5577 Å emissions arise from a parent metastable state with a lifetime of about 0.75 seconds [Chamberlain, 1961] and in general this temporal resolution is more than sufficient.

All the techniques of photometer design were proven satisfactory by the eighteen months' flight test of the Injun I photometer.

APPENDIX II

Photometer Calibrations

Preflight calibrations were performed in the usual two-stage process of first, finding the variation of counting rate as a function of intensity on an arbitrary intensity scale and second, determining the counting rate for known absolute intensities. The absolute intensities discussed in this note are expressed in units of the rayleigh [Hunten, Roach, and Chamberlain, 1956] corresponding for practical purposes to a flux of 10^6 photons cm^{-2} sec^{-1}.

The variation of counting rate with intensity was derived over a range of intensities of more than one million by placing neutral-density filters between each photometer and a steady source of light. The points obtained were reproducible within $\pm$ 20%. The results were checked with a point source of light located at varied distances from the photometer, so that an inverse square law could be applied. The methods gave consistent results within the above limits. The shape of the curves is roughly the same for each of the three photometers. The response is nearly linear up to a sharp breaking point (between 400 and 800 counts per second depending on the unit), above which the counting rate changed less rapidly with the same proportional change in intensity.

Note that a digital system of telemetry is used, so that there is essentially no "reading error". For example, if 3569 counts are accumulated in the register, precisely this number is telemetered to the ground and printed by the computer. With a standard light source causing such a rate in ground checkout, the printed number would vary by only one or two in several hundreds or thousands, and by zero or one in several tens of counts.

The absolute calibrations were determined before launch by means of a radioactive standard light source from U. S. Radium Corporation. When recalibrated in April, 1963, this had a brightness of about 300 rayleighs per Angstrom (R/Å) in the region of 5600 Å. Cross calibrations with a source of the National Bureau of Standards (NBS) late in 1962 agreed with those above to within 10%. However a recent recalibration of the NBS source indicated that original values were too large by a factor of 5/3 [L. Smith, private communication]. Thus the intensities quoted may be too large by this factor. In-flight calibrations as yet cannot resolve this discrepancy.

The method of absolute calibration preflight was to mount the U. S. Radium Corporation source on a spare optical system, complete with a 5577 Å filter. A 4% transmission neutral density filter was added to reduce the light level to the linear range of the photometers. This system was substituted for the optical system of each photometer in turn, and the photometer rates were read out through the complete telemetry, receiving, decoding, and computer system in the usual ways, as well as directly from the photometers alone. Then to obtain absolute calibration of the 5577 Å photometers a simple small correction was made for the difference between the transmission characteristics of the filters. For the 3914 Å photometer an additional correction was made, using the manufacturer's calibration of the photomultiplier response as a function of wavelength.

We can use the preflight relative intensity calibrations to calculate a "true" counting rate even when the photometer is operating in the non-linear region. Thus the true and apparent rates are approximately the same for rates less than some 400 counts per second. Then the preflight absolute calibrations showed that the number of rayleighs of the appropriate spectral emission required to give a true counting rate of 1 count per second were 40 rayleighs and 4 rayleighs for the Northern Hemisphere 5577 Å and 3914 Å photometers, respectively. Thus the 3914 Å photometer was ten times more sensitive than the 5577 Å, if it was assumed that the N_2^+ emission was a line at 3914 Å. In fact it is, of course, a band whose head is at 3914 Å, and so the sensitivity of the 3914 Å photometer to the N_2^+ emission will be somewhat less than the above value (see Figure 1 for the filter spectral passband).

Verification that preflight calibrations are applicable to inflight operation early in 1963, has not yet been completed. Doubt that they can be is raised by data such as in Figure 8, where the counting rate of the 5577 Å photometer remains roughly twice that of the 3914 Å photometer. From the above preflight calibrations, this would imply that the intensity of the 5577 Å emission was twenty times that of the "line" at 3914 Å, or say, ten times that of the N_2^+ band with its head at 3914 Å. Ground-based studies indicate that although this may be about the ratio found in airglow, the ratio in auroras is closer to one or two [see Chamberlain, 1961; Hunter, 1955; Bates, 1960]. If we choose the factor of two, then we have a discrepancy between the two photometers of a factor of five, i.e., the 3914 Å photometer seems to be five times less sensitive (or the 5577 Å photometer more sensitive) in flight than the preflight calibrations would indicate. In practice a photometer may suffer a loss in sensitivity by a factor of about five if it loses one stage of multiplication (as did a spare unit for the Injun I photometer during vibration tests), but it is unlikely that a photometer would increase its sensitivity by a similar factor.

Therefore, it appears that the most likely calibrations for the Northern Hemisphere photometers should be taken to be:

1 true count per 40 rayleighs of 5577 Å line.

1 true count per 20 rayleighs of 3914 Å band.

Clearly these calibrations are less than satisfactory, and they are being refined with later low-altitude dark passes measuring the moon, starlight, and 5577 Å. The uncertainties are greatest with the 3914 Å photometer, and for convenience we summarize below its sensitivity calculated from various assumptions:

1 count/sec for 4 R from preflight treating 3914 Å as a line.
1 count/sec for 8 R from preflight treating 3914 Å band.
1 count/sec for 40 R from inflight if $\frac{I\ (5577\ \text{Å})}{I\ (3914\ \text{Å})} = 2{:}1$.

Hence, we adopt a calibration of ~ 1 count/sec for $(20\ ^{+40}_{-15})$ rayleighs in flight, for the 3914 Å photometer.

This sensitivity estimate is the one used to derive the average maximum intensity of 3914 Å in the auroral zone of 2 KR. This value is in agreement with that predicted from the average precipitated particle flux, but the latter is an average of such greatly variable fluxes that it should not be considered as accurate to better than a factor of about three (see text).

It is interesting to note that this same subject of the ratio of intensities of 5577 Å to 3914 Å in auroras has long been a problem in ground-based measurements [see discussion by Bates, 1960]. Thus some reported values of the ratio have been adjusted by multiplying the 3914 Å observed intensity by a factor of ten. The ratio then comes out to be near unity. It is reported that the ratio is ten or more in airglow [see discussion by Chamberlain] and the difference from unity is taken to be an important indication of the different origin of auroras and airglow. We agree with Roach [private communication] that measurement of the ratio accurately in auroras and airglow is extremely important.

In summary, the only reason we have for doubting the validity of the preflight calibrations is that they would imply that 5577 Å is some ten times more intense than 3914 Å in auroras, and this ratio is apparently inconsistent with previous measurements [Chamberlain, 1961; Bates, 1960]. Preliminary calibrations in flight using starlight [see Roach, 1956] and the full moon indicate that the preflight calibrations were accurate and that the sensitivity inflight was the same as it was preflight.

APPENDIX III

Contamination of the Photometric Studies

Ground-based auroral and airglow studies can be contaminated by scattered sunlight, moonlight, or man-made light, and by starlight or other extraterrestrial light, and can be obscured by clouds.

Satellite-based studies cannot be obscured by clouds, of course (although as Injun I showed another satellite can be even more opaque). However, they can be contaminated in many ways, which we list as follows:

1. By sunlight scattering off the atmosphere or portions of the satellite;
2. By similar moonlight effects;
3. By reflection from the earth;
4. By lightning;
5. By man-made lights;
6. By x-ray bombardment of the photometers producing enhanced "dark" current; and
7. By heating of the photometers producing enhanced dark current.

We eliminated from the following studies the first effect by considering data only when the sun was at least 18° below the horizon of the subsatellite point and when the satellite itself was in the shadow of the earth.

We minimized the second effect by considering data generally from periods when the moon was less than one-quarter full.

The earth reflects some 50% of light incident on it if it is snow or cloud covered, thus the reflection of auroral light may increase the intensity observed by the photometers by almost 50%. Variations in the reflectivity can then cause distortions of the intensity profile of the aurora. Reflected starlight is negligible since the starlight itself is negligible.

The resolution of the telemetry and concentration on Arctic passes are sufficient to exclude significant contamination by lightning.

We excluded the fifth effect by considering for low-intensity studies, only data acquired over regions of low-population density, such as the Hudson Bay. In any event, man-made lights produced a distinctive small and brief effect, which could be proven to be man-made by simply referring to the ephemeris and checking whether a city was at the base of the magnetic field line along which the satellite was pointed. This served a useful purpose also in checking the accuracy of the N.A.S.A. orbit, since the locations of such cities as New York are known accurately. Figure 3 shows a typical example of the detection of New York in a northbound pass which then took the satellite over Boston. It is clear from this figure that the lights of Boston are less intense than those of New York at 2 a.m., as one would expect.

This figure is also a typical example of the sixth effect, the enhanced "dark" current of a photometer due to its previous bombardment by x-rays or electrons, and the gradual recovery of the "dark" current to normal. In anticipation of this effect, we endeavored to minimize it by encasing the photomultipliers in lead 0.010 inches thick. We then experimentally determined the quantitative effects of x-ray bombardment by subjecting the flight-unit photometers to x-ray beams of varying intensities over energies varied from 40 keV to 250 keV. For example, a flux of order 10^9 cm^{-2} sec^{-1} of 100 keV electrons is needed to give a photometer signal of the same magnitude as that given by 5577 Å airglow. From similar calibrations of particle detectors on the satellite, one can conceivably estimate the actual effect of a given exposure in flight. However, in practice we have not done this. The great ellipticity of the orbit has increased the x-ray exposure to such a level on occasions that, even minutes later (as in Figure 3) the dark current has not recovered to normal.

In practice we determine from the upward-pointing photometer(s) in each case whether there is any such x-ray effect, and do not use data at such times. The altitude at which the satellite most recently passed through the artificial belt is known in each case, as is the elapsed time since it made such a passage, and so by choosing passes when the former number is small and the latter large, one can study low-intensity phenomena.

The seventh effect is minimized by our thermal control of the satellite [O'Brien et al., 1963] which kept the temperature of the photometers between about 4° C and 28° C. In addition, since photometric data were obtained when the satellite itself was in the earth's shadow and hence cold, the dark currents were low at times of interest. Furthermore, the temperature of one of the photometers is measured every four seconds in System A, and one can then quantitatively estimate the dark current.

The major contamination of our data, and the least amenable to quantitative estimation, has been the long-duration effects of x-ray bombardment in the artificial radiation belt. In this note we consider only auroras, rather than the weaker airglow, and since the electron fluxes causing these auroras are relatively soft, they do not themselves produce any instantaneous much less any long-lived enhancement of the photometer signals through direct bombardment of the photometers. This can be shown quantitatively in every case by studying the upward-looking photometer. For example, see text for discussion of two passes where the change in signal from the upward pointing detector was less than 0.1% of that of the others. Furthermore, the auroras are relatively bright and they produce a photometer signal large compared with the dark current. For quantitative study here, the plateau dark current both on the low-latitude side and on the high-latitude side of each auroral event is subtracted from the signal in the auroral event. Thus, not only dark current but also airglow effects are subtracted, leaving essentially the pure auroral effect. This technique is discussed and illustrated for particular events in the text (e.g., see Figure 3).

The photometers recover to dark current within less than a second after viewing a bright aurora. They take tens of minutes to make a similar recovery if they were switched on and viewed the sunlit earth. In all this study, any such effects have been eliminated by subtraction of the "background" signal, as discussed above.

REFERENCES

Anderson, Kinsey A., Balloon observations of x-rays in the auroral zone I, J. Geophys. Res., 65, 551-564, 1960.

Anderson, K. A., and R. DeWitt, Space-time association of auroral glow and x-rays at balloon altitude, J. Geophys. Res., 68, 2669-2676, 1963.

Arnoldy, R. L., R. A. Hoffman, J. R. Winckler, and S.-I. Akasofu, Observations of the Van Allen radiation regions during August and September 1959. V. Visual auroras, high-altitude x-ray bursts and simultaneous satellite observations, J. Geophys. Res., 67, 3673-3686, 1962.

Bates, D. R., Physics of the Upper Atmosphere, ed. by J. A. Ratcliffe, pp. 307-308, Academic Press, New York (1960).

Brown, R. R., Balloon observations of auroral-zone x-rays, J. Geophys. Res., 66, 1379-1388, 1961.

Brown, R. R., K. A. Anderson, C. D. Anger, and D. S. Evans, Simultaneous electron precipitation in the northern and southern auroral zones, J. Geophys. Res., 68, 2677-2684, 1963.

Chamberlain, J. W., Physics of the Aurora and Airglow, Academic Press, New York, 1961.

Davis, L. R., O. E. Berg, and L. H. Meredith, "Direct measurements of particle fluxes in and near auroras", Space Research I, Proc. Intern. Space Sci. Symp., 1st, Nice, 1960, ed. by H. K. Kallmann-Bijl, pp. 721-735, North-Holland Publishing Company, Amsterdam (1960).

Davis, T. N., The morphology of the auroral displays of 1957-1958, Parts I and II, J. Geophys. Res., 67, 59-110, 1962.

Gurnett, D. A., and B. J. O'Brien, High-latitude geophysical studies with satellite Injun III, Part V: Very low frequency (VLF) electromagnetic radiation, J. Geophys. Res. (in course of publication).

Hunten, D. M., Some photometric observations of auroral spectra, J. Atmospheric Terrest. Phys., 7, 141-151, 1955.

Hunten, D. M., F. E. Roach, and J. W. Chamberlain, A photometric unit for the airglow and aurora, J. Atmospheric Terrest. Phys., 8, 345, 1956.

Laughlin, C. D., T. Fritz, and D. E. Stilwell, High-latitude geophysical studies with satellite Injun III, Part II: Intensities and spectra of trapped electrons, J. Geophys. Res. (in course of publication).

McIlwain, C. E., "Direct measurements of protons and electrons in visible aurorae", Space Research I, Proc. Intern. Space Sci. Symp., 1st, Nice, 1960, ed. by H. Kallmann-Bijl, pp. 715-720, North-Holland Publishing Company, Amsterdam (1960).

McIlwain, C. E., Coordinates for mapping the distribution of magnetically trapped particles, J. Geophys. Res., 66, 3681-3692, 1961.

O'Brien, B. J., Lifetimes of outer-zone electrons and their precipitation into the atmosphere, J. Geophys. Res., 67, 3687-3706, 1962.

O'Brien, B. J., A large diurnal variation of the geomagnetically-trapped radiation, J. Geophys. Res., 68, 989-996, 1963.

O'Brien, B. J., High-latitude geophysical studies with satellite Injun III, Part III: Precipitation of electrons into the atmosphere, J. Geophys. Res. (in course of publication).

O'Brien, B. J., C. D. Laughlin, and D. A. Gurnett, High-latitude geophysical studies with satellite Injun III, Part I: Description of the satellite, J. Geophys. Res. (in course of publication).

O'Brien, B. J., J. A. Van Allen, F. E. Roach, and C. W. Gartlein, Correlation of an auroral arc and a subvisible monochromatic 6300 Å arc with outer-zone radiation on November 28, 1959, J. Geophys. Res., 65, 2759-2766, 1960.

Omholt, Anders, Observational and experimental tests of auroral theories, Planetary Space Sci., 10, 247-262, 1963.

Roach, F. E., Manual for photometric observations of the airglow during the I.G.Y., National Bureau of Standards Report 5006, 1956.

Roach, F. E., W. McCaulley, E. Marovitch, and C. M. Purdy, A comparative study of absolute zenith intensities of [O I] 5577, J. Geophys. Res., 65, 1503-1512, 1960.

Van Allen, J. A., Direct detection of auroral radiation with rocket equipment, Proc. Natl. Acad. Sci. U. S., 43, 57-92, 1957.

Van Allen, J. A., and L. A. Frank, Radiation measurements to 658,300 km with Pioneer IV, Nature (London), 184, 219-224, 1959.

Van Allen, J. A., C. E. McIlwain, and G. H. Ludwig, Radiation observations with satellite 1958 epsilon, J. Geophys. Res., 64, 271-286, 1959.

Vestine, E. H., The geographic incidence of aurora and magnetic disturbance, Northern Hemisphere, Terr. Mag., 49, 77-102, 1944.

Vestine, E. H., and W. L. Sibley, The geomagnetic field in space, ring currents, and auroral isochasms, J. Geophys. Res., 65, 1967-1979, 1960.

Winckler, J. R., Atmospheric phenomena, energetic electrons and the geomagnetic field, Technical Report No. CR-40, University of Minnesota, 1961.

FIGURE CAPTIONS

Figure 1. Spectral resolution of the three multilayer interference filters for light at normal incidence. Detectors 16 and 17 point down and detector 18 points up in the Northern Hemisphere.

Figure 2. Angular field of view of a typical Injun III photometer. All photometers have similar optical systems. Note the logarithmic scale of the relative response.

Figure 3. Counting rate of the 3914 Å photometer in an oriented northbound pass over North America. This shows the recovery of the dark current after intense x-ray and electron bombardment in the Starfish artificial radiation belt, a small increase at 06.39 U.T. as the magnetic dip is such that the photometer views the horizon, and then the response to lights from two cities. The light from New York can be estimated from the dotted minus the dashed line. Each dot is a measured point.

Figure 4. Three sample latitude profiles of 3914 Å light. The plotted rates are those obtained after an interpolated background has been subtracted (see Figure 3). The intensity corresponding to 50 counts per frame is about (4^{+8}_{-35}) kilorayleighs (see Appendix II).

Figure 5. Intensity of 3914 Å auroral light averaged over four seconds at half-integral values of L in about fifty passes early in 1963. In each case the background signal has been subtracted (see text). The vertical scale is that derived from calibrations assuming a sensitivity of 20 R per count/sec [see Appendix II]. The visual threshold shown is at 500 R of 3914 Å, corresponding to 1 KR of 5577 Å on the above calibrations. This is the intensity of 5577 Å in an IBC I aurora.

Figure 6. Summary of 3914 Å auroral data from Figure 5. The curve plotted from Vestine [1944] for visual observations is plotted here as if geomagnetic latitude and invariant latitude are the same.

Figure 7. Sketches of two auroras mapped out by the 5577 Å photometer in two successive passes over North America. Note the size of the area viewed by the photometer, and also the constant intensity of 5577 Å airglow observed on the low- and high-latitude portions of the passes away from the auroras. The intensity corresponding to about 50 counts per frame is about 8 kilorayleighs. Visual threshold is about 6 counts per frame.

Figure 8. Relative counting rates of 5577 Å and 3914 Å photometers plotted for each interval of two seconds during the auroras of Figure 7. The background counting

rate (due to airglow plus dark current) was subtracted before the points were plotted. The line has a slope of 45°, and corresponds to the brightness of 5577 Å in rayleighs being twice that of 3914 Å [see Appendix II].

Figure 9. Data from a northbound pass of Injun III over North America, which shows simultaneous detection of an aurora, of the precipitated electrons (with $\alpha = 50°$) partially responsible for causing it, and of trapped electrons. Note the approach to isotropy of the particle flux over the aurora. No attempt has been made to subtract the low-latitude contamination of the photometer signal, part of which was the detection of Cleveland, Ohio and its surroundings. Not all the detailed rapid variations of particle fluxes are shown. The preliminary intensity scale of the photometer is that derived from a sensitivity of 4 R per count/sec, and it is likely to be low [see Appendix II].

Figure 10. Similar to that of Figure 9, except that the flux of electrons with pitch-angle $\alpha \sim 0°$ is plotted in place of the flux with $\alpha \sim 50°$, and that a correction to the photometer signal has been made for background.

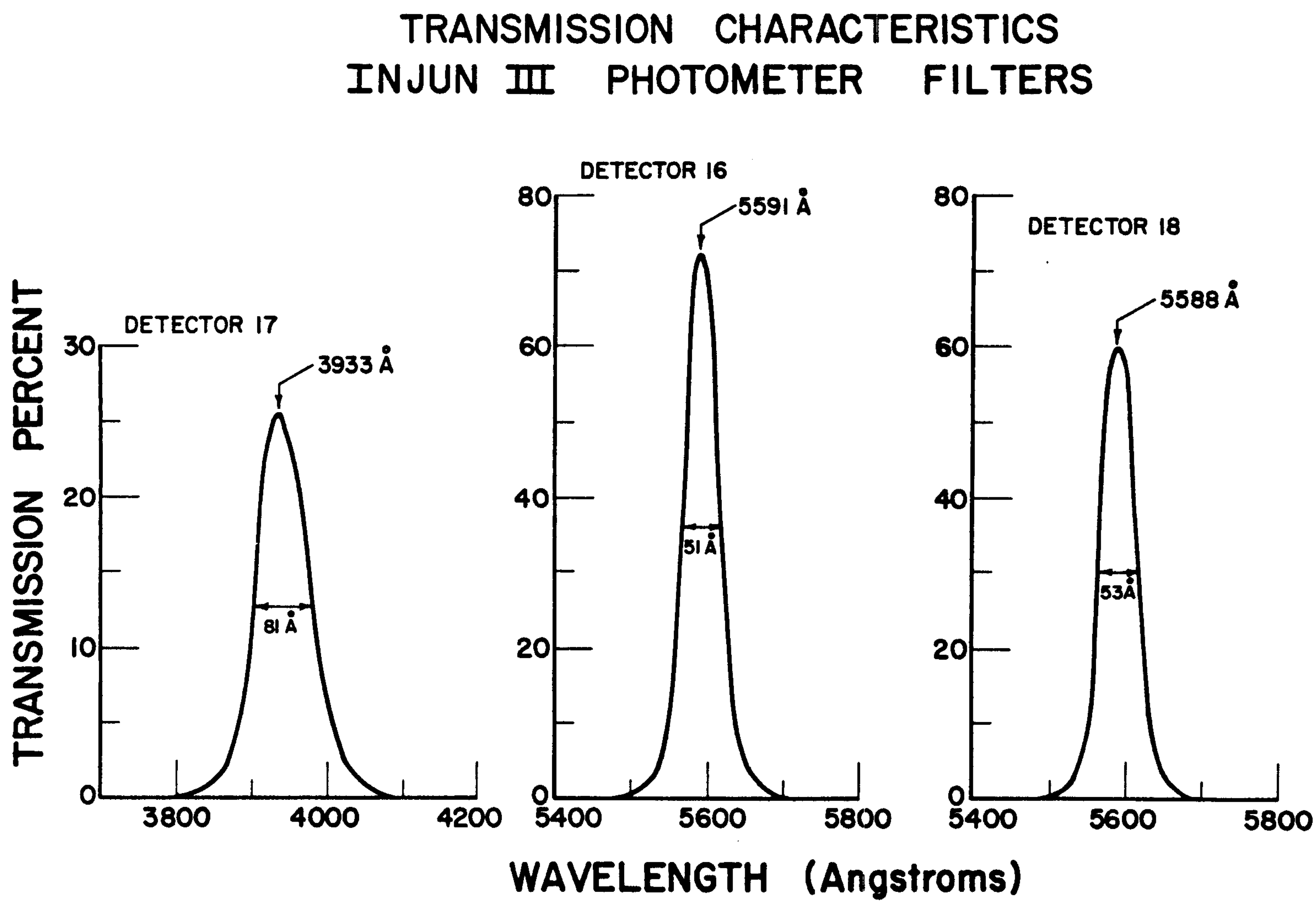
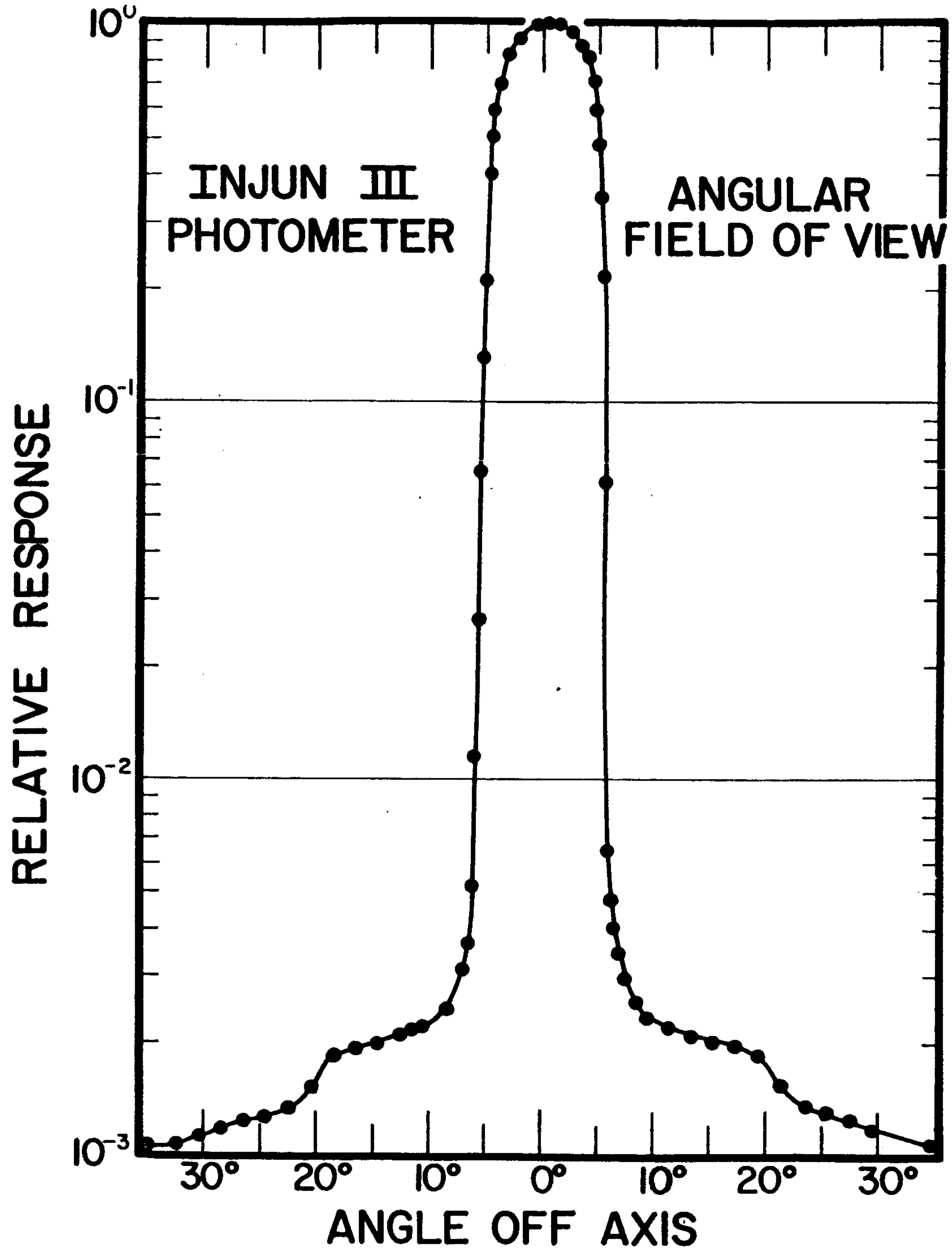

TRANSMISSION CHARACTERISTICS
INJUN III PHOTOMETER FILTERS
TRANSMISSION PERCENT
DETECTOR 17
3933 Å
81 Å
30
20
10
0
3800
4000
4200
DETECTOR 16
5591 Å
51 Å
80
60
40
20
0
5400
5600
5800
DETECTOR 18
5588 Å
53Å
80
60
40
20
0
5400
5600
5800
WAVELENGTH (Angstroms)

Figure 1



INJUN III
PHOTOMETER
ANGULAR
FIELD OF VIEW
RELATIVE RESPONSE
10^0
10^{-1}
10^{-2}
10^{-3}
30°
20°
10°
0°
10°
20°
30°
ANGLE OFF AXIS

Figure 2

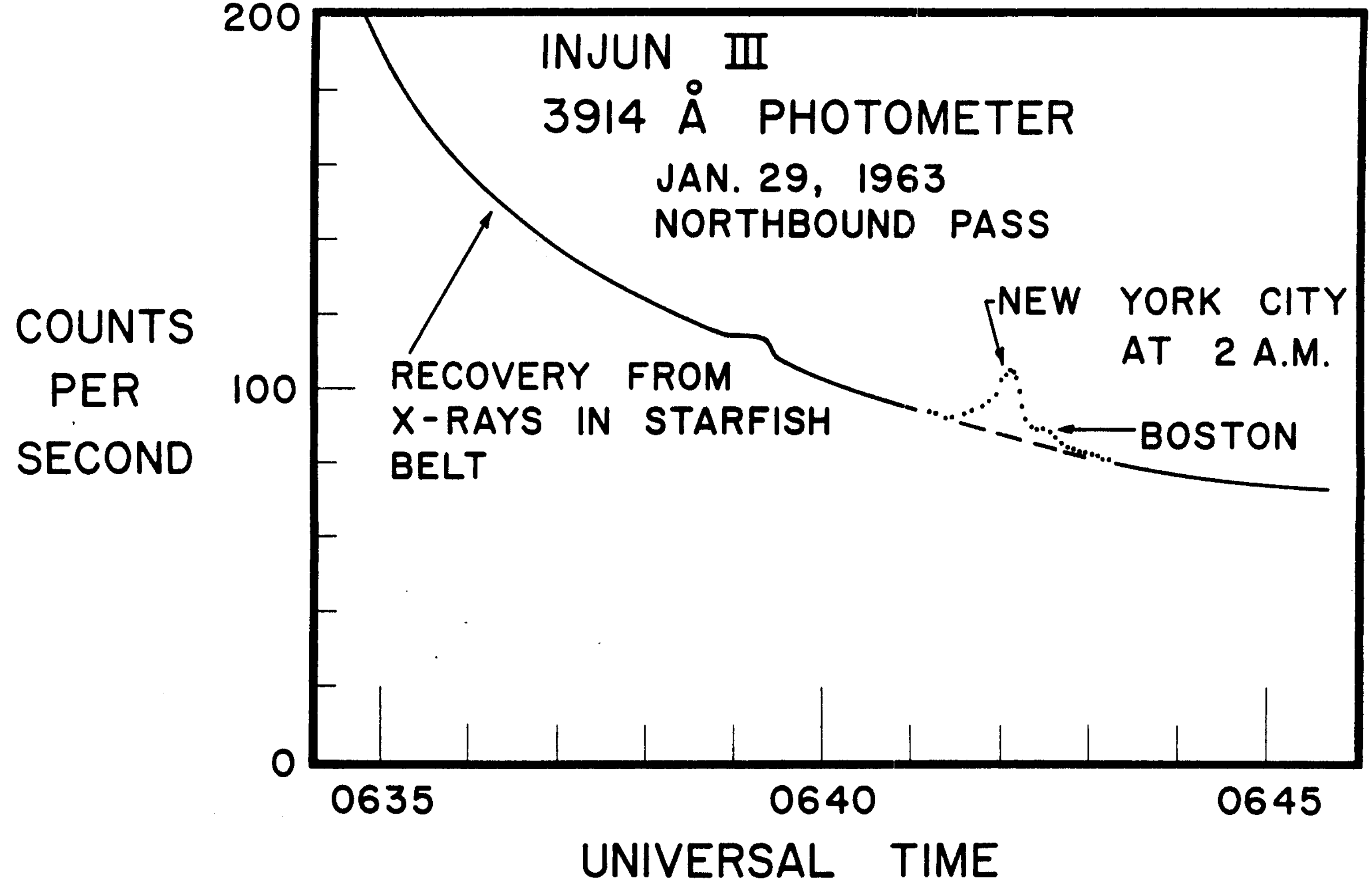
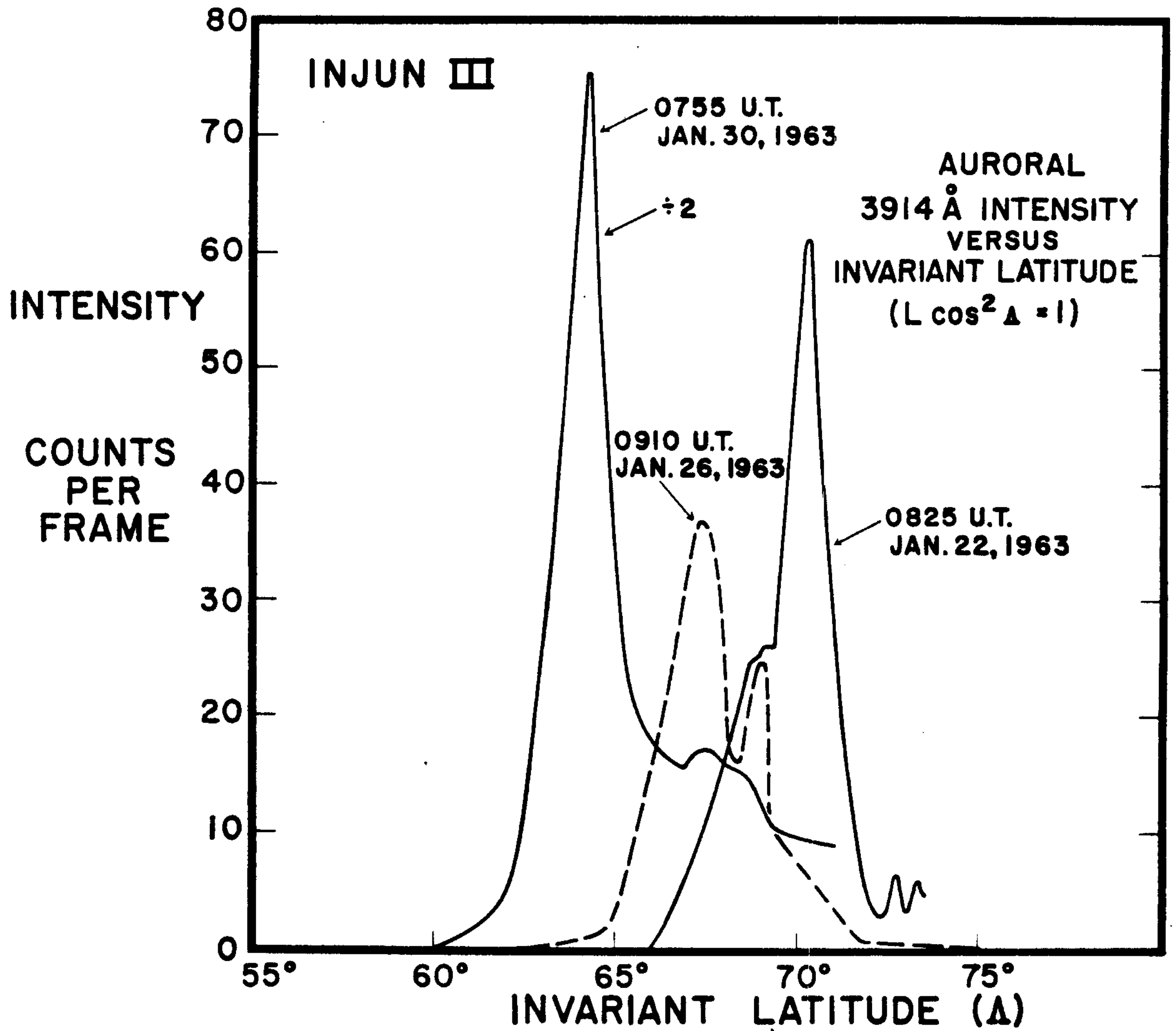

INJUN III
3914 Å PHOTOMETER
JAN. 29, 1963
NORTHBOUND PASS
COUNTS PER SECOND
200
100
0
RECOVERY FROM X-RAYS IN STARFISH BELT
NEW YORK CITY AT 2 A.M.
BOSTON
0635
0640
0645
UNIVERSAL TIME

Figure 3



INJUN III
0755 U.T.
JAN. 30, 1963
÷2
AURORAL
3914 Å INTENSITY
VERSUS
INVARIANT LATITUDE
(L cos² Λ = 1)
0910 U.T.
JAN. 26, 1963
0825 U.T.
JAN. 22, 1963
INTENSITY
COUNTS
PER
FRAME
80
70
60
50
40
30
20
10
0
55°
60°
65°
70°
75°
INVARIANT LATITUDE (Λ)

Figure 4

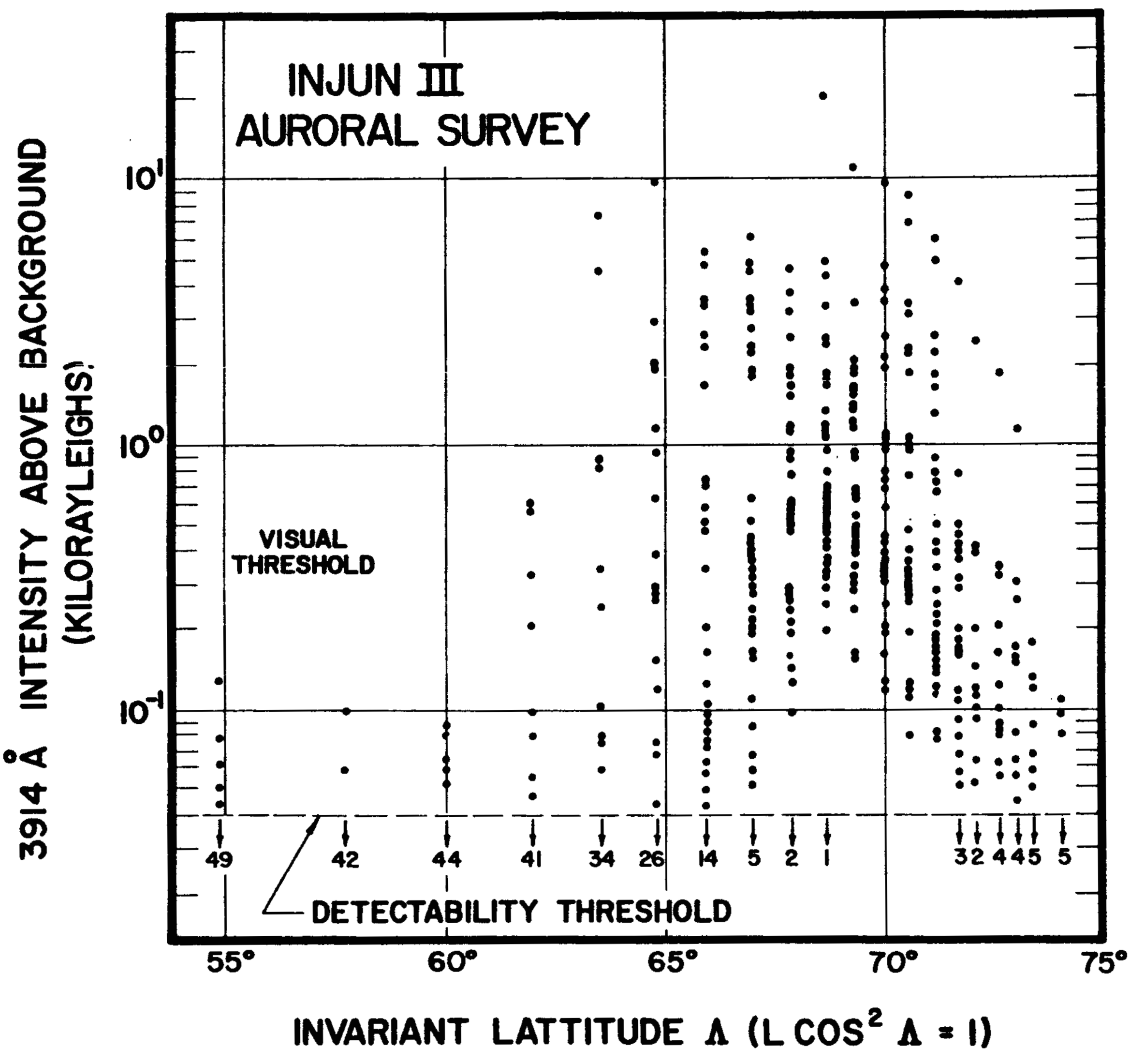

INJUN III
AURORAL SURVEY
VISUAL THRESHOLD
DETECTABILITY THRESHOLD
10^1
10^0
10^{-1}
3914 Å INTENSITY ABOVE BACKGROUND (KILORAYLEIGHS)
49
42
44
41
34
26
14
5
2
1
3
2
4
4
5
5
55°
60°
65°
70°
75°
INVARIANT LATTITUDE Λ (L COS² Λ = 1)

Figure 5

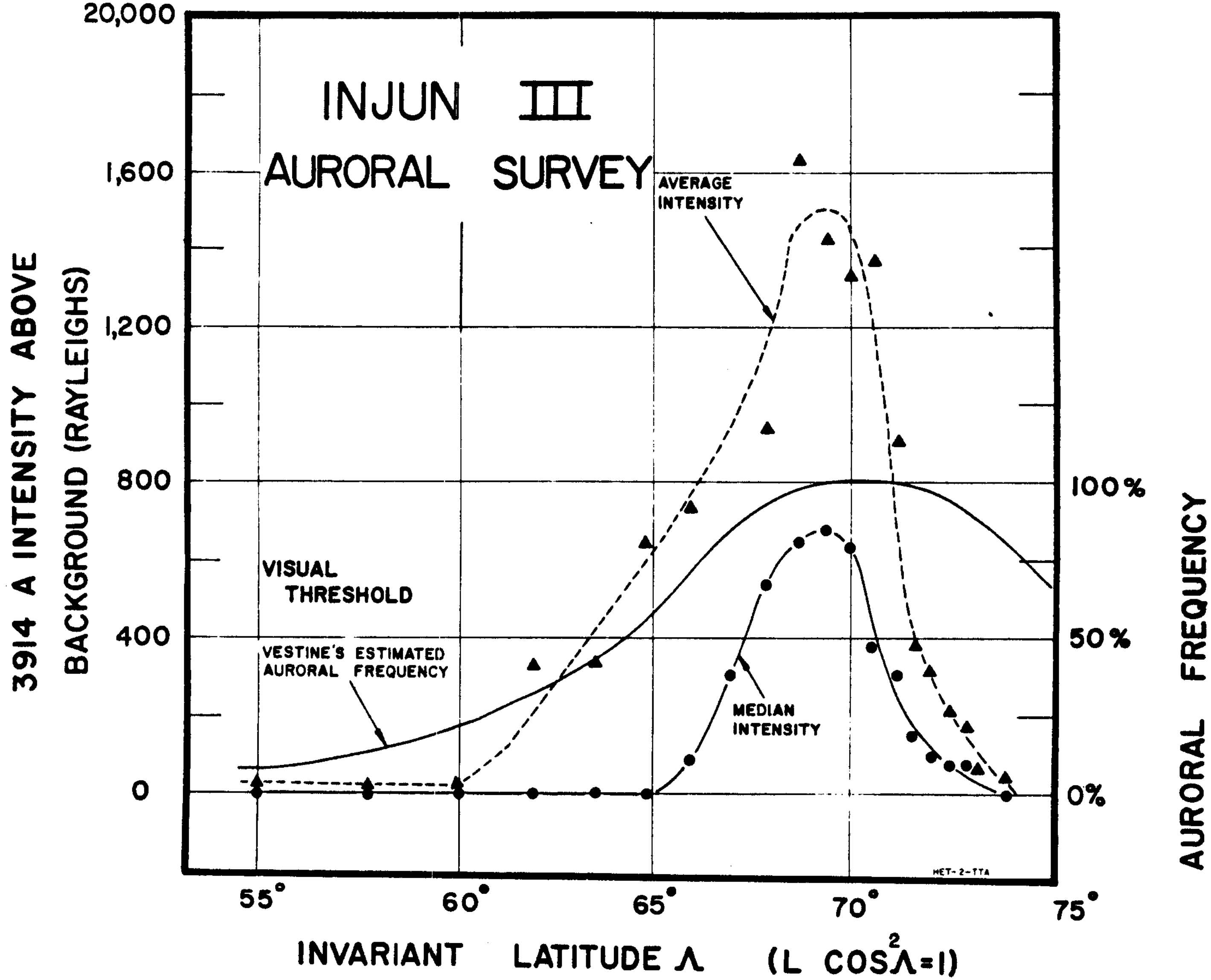

INJUN III
AURORAL SURVEY
AVERAGE INTENSITY
VISUAL THRESHOLD
VESTINE'S ESTIMATED AURORAL FREQUENCY
MEDIAN INTENSITY
3914 A INTENSITY ABOVE BACKGROUND (RAYLEIGHS)
20,000
1,600
1,200
800
400
0
100%
50%
0%
AURORAL FREQUENCY
55°
60°
65°
70°
75°
INVARIANT LATITUDE Λ (L COS²Λ=1)
MET-2-TTA

Figure 6

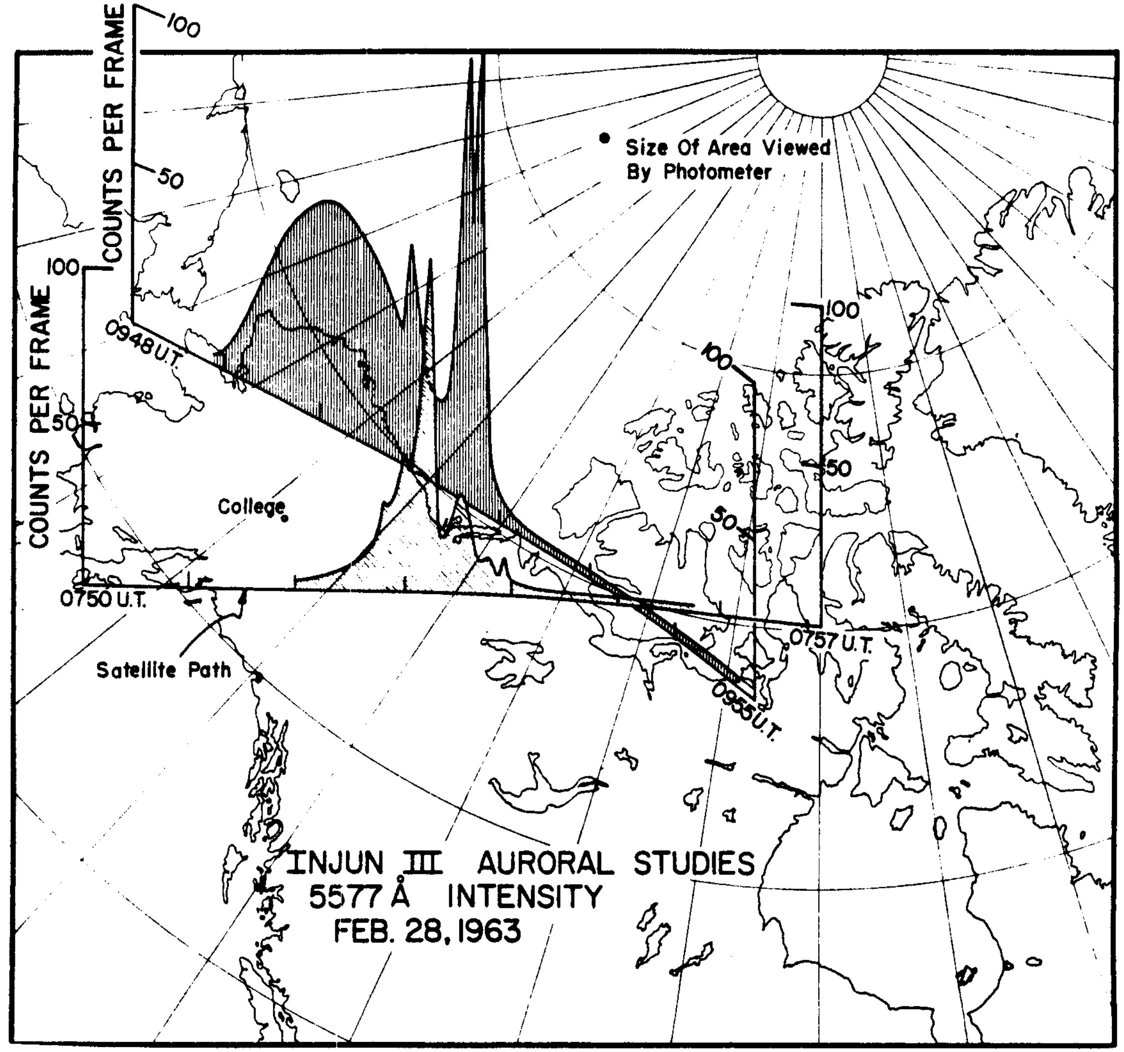

COUNTS PER FRAME
100
50
COUNTS PER FRAME
100
50
0948 U.T.
0750 U.T.
College
Satellite Path
Size Of Area Viewed
By Photometer
100
50
100
50
0757 U.T.
0955 U.T.
INJUN III AURORAL STUDIES
5577 Å INTENSITY
FEB. 28, 1963

Figure 7

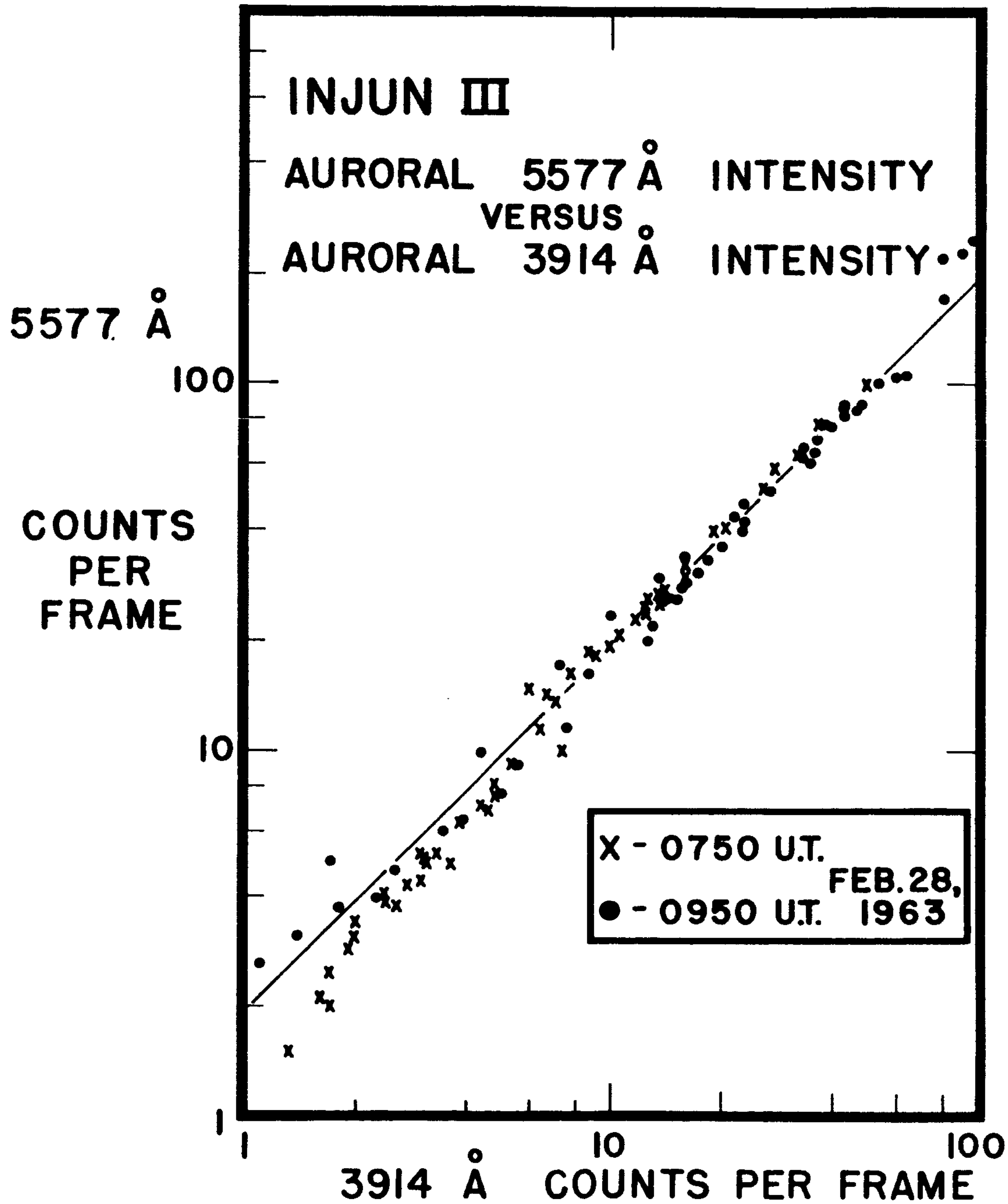

INJUN III
AURORAL 5577 Å INTENSITY
VERSUS
AURORAL 3914 Å INTENSITY
5577 Å
COUNTS
PER
FRAME
100
10
1
1
10
100
3914 Å COUNTS PER FRAME
X - 0750 U.T.
FEB. 28,
● - 0950 U.T. 1963

Figure 8

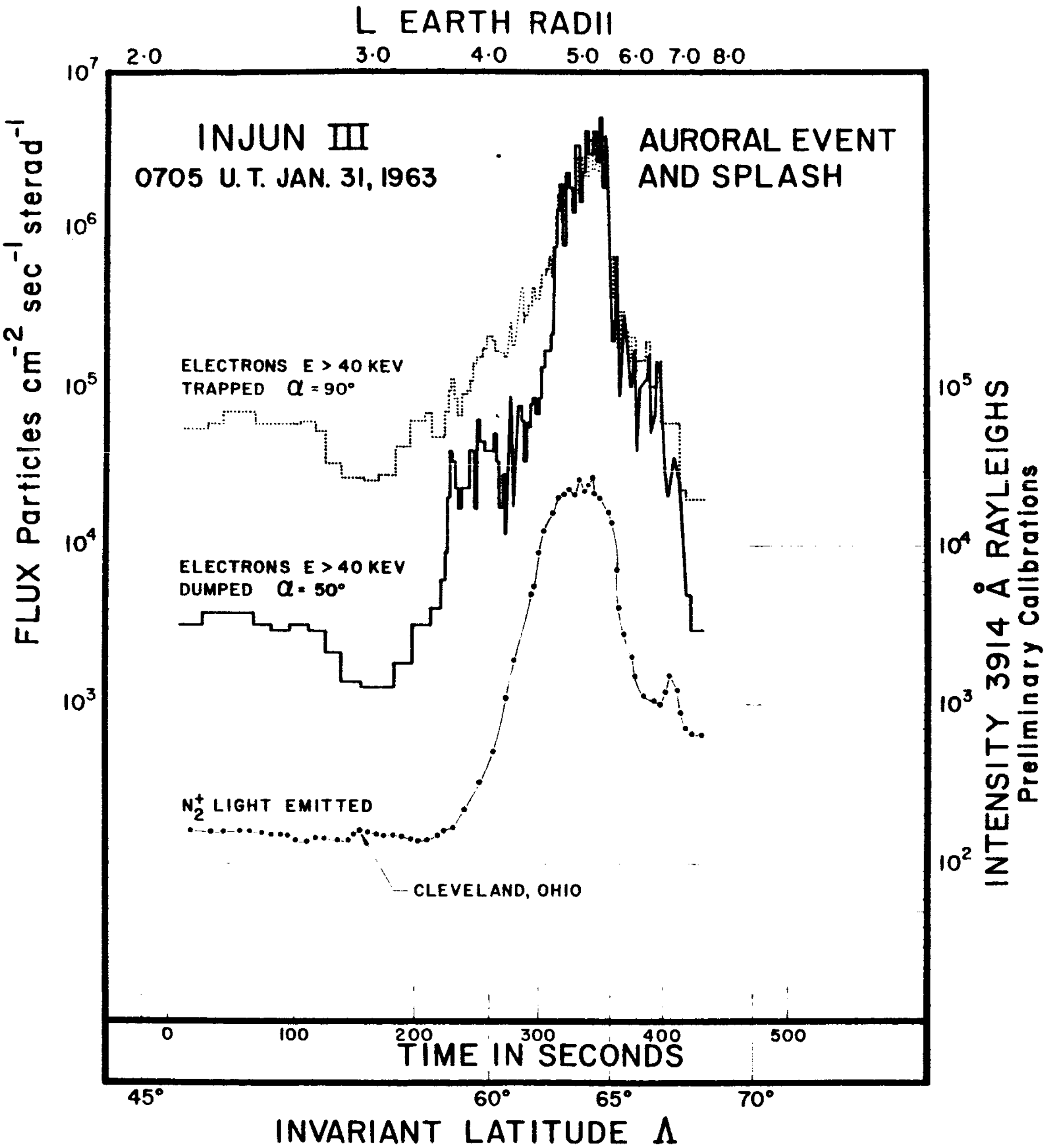

L EARTH RADII
2·0 3·0 4·0 5·0 6·0 7·0 8·0
INJUN III
0705 U.T. JAN. 31, 1963
AURORAL EVENT AND SPLASH
ELECTRONS E > 40 KEV TRAPPED α = 90°
ELECTRONS E > 40 KEV DUMPED α = 50°
N2+ LIGHT EMITTED
CLEVELAND, OHIO
FLUX Particles cm-2 sec-1 sterad-1
INTENSITY 3914 Å RAYLEIGHS
Preliminary Calibrations
0 100 200 300 400 500
TIME IN SECONDS
45° 60° 65° 70°
INVARIANT LATITUDE Λ

Figure 9

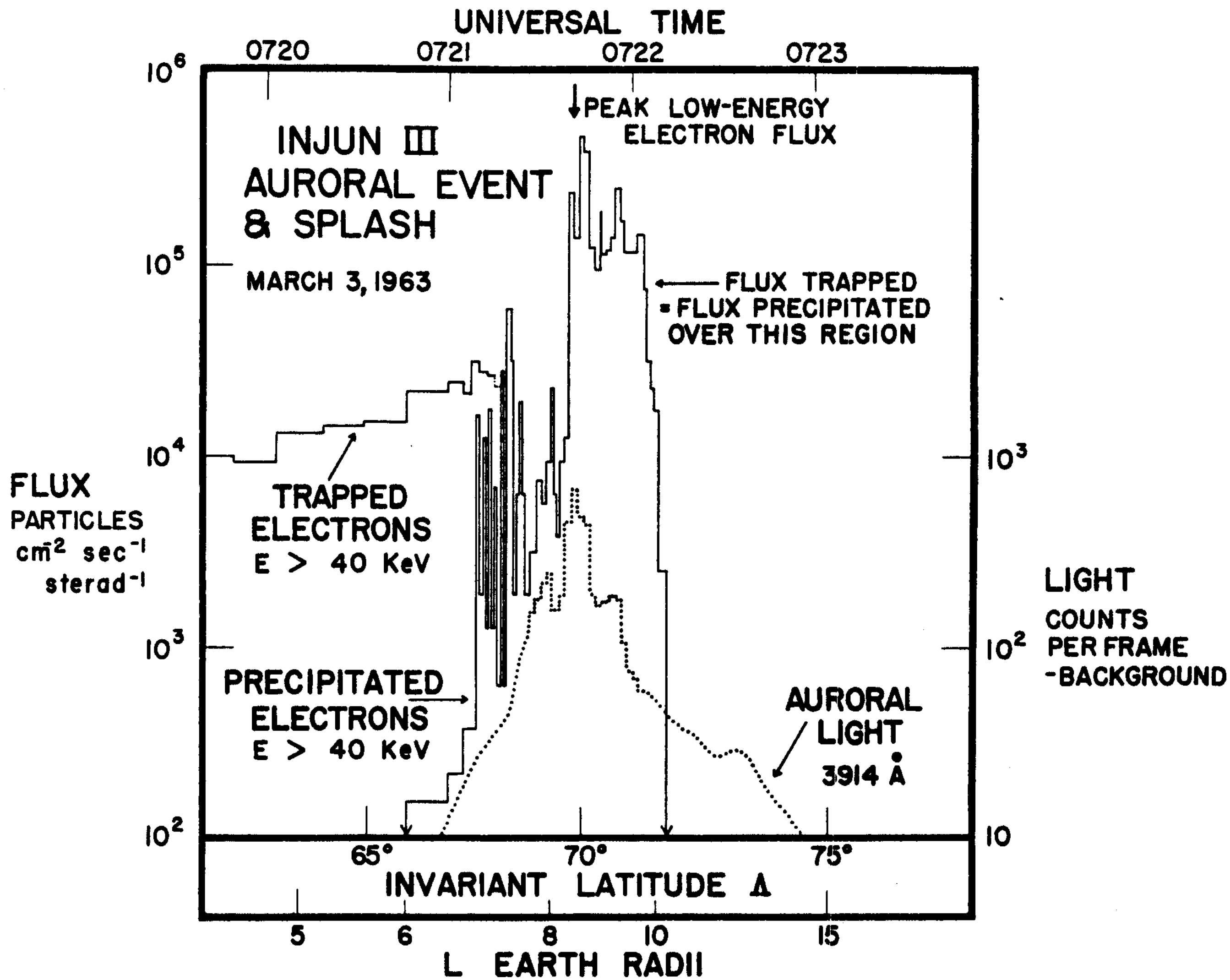

UNIVERSAL TIME
0720
0721
0722
0723
10^6
10^5
10^4
10^3
10^2
FLUX
PARTICLES
cm^-2 sec^-1
sterad^-1
INJUN III
AURORAL EVENT
& SPLASH
MARCH 3, 1963
PEAK LOW-ENERGY
ELECTRON FLUX
FLUX TRAPPED
= FLUX PRECIPITATED
OVER THIS REGION
TRAPPED
ELECTRONS
E > 40 KeV
PRECIPITATED
ELECTRONS
E > 40 KeV
AURORAL
LIGHT
3914 Å
10^3
10^2
10
LIGHT
COUNTS
PER FRAME
-BACKGROUND
65°
70°
75°
INVARIANT LATITUDE Λ
5
6
8
10
15
L EARTH RADII

Figure 10

TABLE I

Characteristics of Injun III Photometers

Detector	Wavelength of Spectral Emission	Origin of Emission	Viewing Direction in Arctic
Number 16	5577 Å	[O I]	Down
Number 17	3914 Å	N_2^+	Down
Number 18	5577 Å	[O I]	Up